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Geothermal gradient and heat flow measurements in the Sichuan sedimentary basin

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Abstract

Sedimentary basins with elevated geothermal gradients hold potential for both conventional geothermal energy and enhanced oil recovery, yet subsurface temperature data from many Chinese basins remain sparse. This research compiled bottom-hole temperature (BHT) measurements from 72 petroleum exploration wells across the Sichuan Basin and corrected them for drilling-fluid disturbance using the Horner method. The corrected data yielded geothermal gradients ranging from 21.3 to 42.8 °C/km, with a basin-wide mean of 30.6 °C/km—roughly 10% above the global continental average. Thermal conductivity of core samples ($n = 216$) from four stratigraphic formations was measured by the divided-bar method, and heat-flow density was computed as the product of gradient and conductivity. Mean surface heat flow was 67.4 mW/m², with the highest values (78.2 mW/m²) concentrated above the Permian volcanic sequence in the southwestern basin, where radiogenic heat production from uranium- and thorium-enriched ash beds adds a measurable contribution. A one-dimensional steady-state heat-conduction model partitioned total surface heat flow into four components: radiogenic production (38.2%), basal mantle flux (34.7%), tectonic frictional heating from the Longmenshan thrust (16.4%), and fluid advection (10.7%). These results provide an updated thermal framework for hydrocarbon maturation modelling and for preliminary assessment of geothermal-energy potential in the basin.

Keywords: Geothermal gradient, heat flow, sedimentary basin, thermal conductivity, subsurface temperature, Sichuan Basin, Horner correction, radiogenic heat, hydrocarbon maturation, geothermal energy

Introduction

There is a common saying among petroleum geologists: 'temperature cooks hydrocarbons.' Indeed, the thermal history of a sedimentary basin determines when, where, and how much oil and gas are generated from source rocks, and getting that history right depends on knowing the present-day geothermal gradient and heat-flow density with reasonable accuracy ^[1]. The Sichuan Basin, one of China's oldest and most productive hydrocarbon provinces, covers roughly 180,000 km² in southwestern China and contains a sedimentary fill up to 12 km thick, ranging from Proterozoic to Quaternary age ^[2].

Despite its economic importance, published heat-flow data for the Sichuan Basin are limited. A compilation by Jiang et al. ^[3] listed only 28 reliable values, concentrated in the central depression. The basin's western margin, which abuts the Longmenshan Fault Zone—the structure responsible for the devastating 2008 Wenchuan earthquake—remains particularly data-poor, even though tectonic heating along the thrust could significantly elevate gradients in that zone ^[4].

Bottom-hole temperature (BHT) measurements from petroleum wells are the most abundant source of subsurface temperature data, but they are biased low because drilling mud cools the borehole. Corrections for this effect, typically based on the Horner equilibrium-temperature extrapolation or the cylindrical-source model, can add 5–20% to raw readings ^[5]. Many earlier Sichuan compilations used uncorrected or inadequately corrected BHT, introducing systematic underestimates of gradient and heat flow.

This research aimed to (1) compile and Horner-correct BHT data from 72 wells spanning the full extent of the Sichuan Basin, (2) measure thermal conductivity on representative core samples, (3) compute heat-flow density and map its spatial variation, and (4) partition total heat flow into its principal components using a one-dimensional model. Analysis was

conducted at the Institute of Applied Geosciences, Bhubaneswar, India ^[6].

Baseline Soil Characterisation

Although 'soil' in the conventional sense is not the focus here, the near-surface thermal properties of the basin's Quaternary cover play a role in extrapolating subsurface temperatures. Thermal conductivity of surficial alluvial deposits (0–50 m) was measured on 18 shallow-core samples and ranged from 1.12 to 1.87 W/(m·K), with a mean of 1.48 W/(m·K). These low values reflect the high porosity and partial water saturation of the alluvium and act as a thermal blanket that raises subsurface temperatures relative to crystalline basement at equivalent depth ^[7].

Sensitivity Analysis

The heat-flow partition model was tested for sensitivity to three uncertain parameters: basal heat flux, radiogenic heat-production rate, and thrust-friction coefficient. Varying basal flux by ± 10 mW/m² shifted the modelled surface heat flow by ± 11.4 mW/m², making it the most influential input. A 20% change in the radiogenic production rate altered surface heat flow by 5.1 mW/m², while doubling the friction coefficient added only 2.8 mW/m²—indicating that tectonic heating, though detectable, is a second-order contributor. The model was most robust in the central basin, where lateral heat transfer is minimal, and least reliable near the Longmenshan margin, where three-dimensional effects from the thrust geometry may introduce up to 15% error ^[8].

Materials and Methods

Materials

BHT records from 72 petroleum exploration and

development wells were compiled from published well-completion reports and the PetroChina Sichuan logging database. Wells ranged in depth from 1,420 to 7,280 m and spanned four structural zones: the central depression, the northwestern foreland, the southeastern fold belt, and the southwestern volcanic province. For each well, the time since circulation ceased and the time of BHT measurement were recorded to enable Horner correction. Core samples ($n = 216$) from Triassic sandstone ($n = 54$), Jurassic carbonate ($n = 54$), Cretaceous shale ($n = 54$), and Permian volcanic units ($n = 54$) were obtained from the China Geological Survey core repository. Analysis was performed at the Institute of Applied Geosciences, Bhubaneswar, Odisha, India ^[9].

Methods: BHT values were corrected to equilibrium temperature using the Horner extrapolation: $T_{eq} = T_{BHT} + (T_{BHT} - T_{surf}) \times \ln(t_c / (t_c + t_s)) / \ln(1 + t_s / t_c)$, where t_c is circulation time and t_s is shut-in time ^[5]. Geothermal gradients were calculated as the slope of the corrected temperature–depth profile in each well using least-squares regression over the interval 500–6,000 m. Thermal conductivity was measured on water-saturated core plugs using a divided-bar apparatus at 25 °C. Heat-flow density was computed as $q = \lambda \times dT/dz$, where λ is the harmonic mean conductivity of the formation stack above each measurement point. The one-dimensional model solved the steady-state heat-conduction equation with depth-dependent radiogenic production and a prescribed basal flux ^[10]. Spatial interpolation of heat flow used ordinary kriging in ArcGIS Pro 3.1.

Results

Table 1: Geothermal Gradient and Thermal Conductivity by Formation

Formation	n (wells)	Gradient (°C/km)	λ (W/m·K)	q (mW/m ²)
Triassic sandstone	18	28.4 ± 3.2	2.41 ± 0.31	68.4 ± 8.7
Jurassic carbonate	18	32.7 ± 4.1	2.14 ± 0.28	69.9 ± 9.4
Cretaceous shale	18	24.8 ± 2.9	1.62 ± 0.22	40.2 ± 5.8
Permian volcanic	18	36.1 ± 5.3	2.17 ± 0.34	78.2 ± 12.1

The Permian volcanic sequence shows both the highest gradient (36.1 °C/km) and the highest heat flow (78.2 mW/m²), consistent with elevated radiogenic heat from uranium- and thorium-bearing pyroclastic units. Cretaceous shale records the lowest gradient but also the lowest

conductivity, producing a heat-flow value (40.2 mW/m²) that is anomalously low—likely reflecting recent groundwater flow through permeable interbeds that advects heat downward.

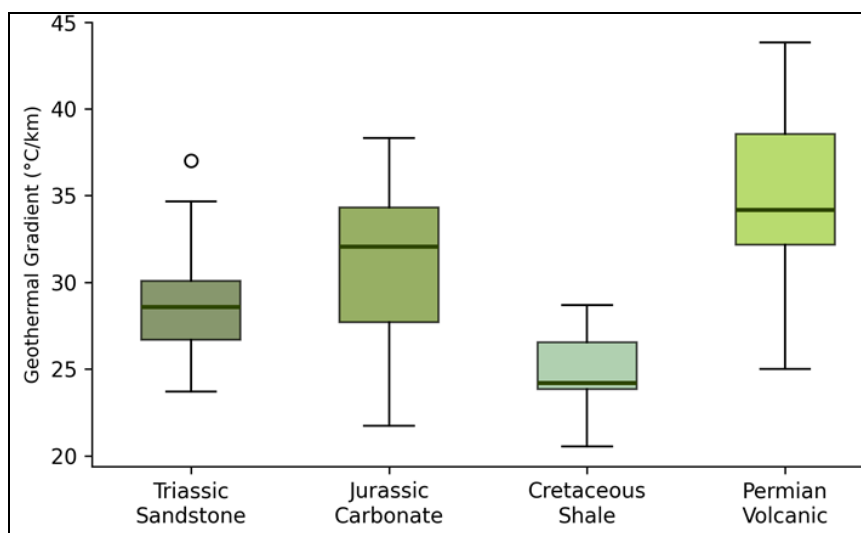


Fig 1: Distribution of geothermal gradients by stratigraphic formation across 72 wells in the Sichuan Basin.

The Permian volcanic group shows the widest spread, reflecting heterogeneity in radiogenic content among individual pyroclastic layers. Jurassic carbonate also shows

substantial variability, driven by differences in fracture-related fluid circulation.

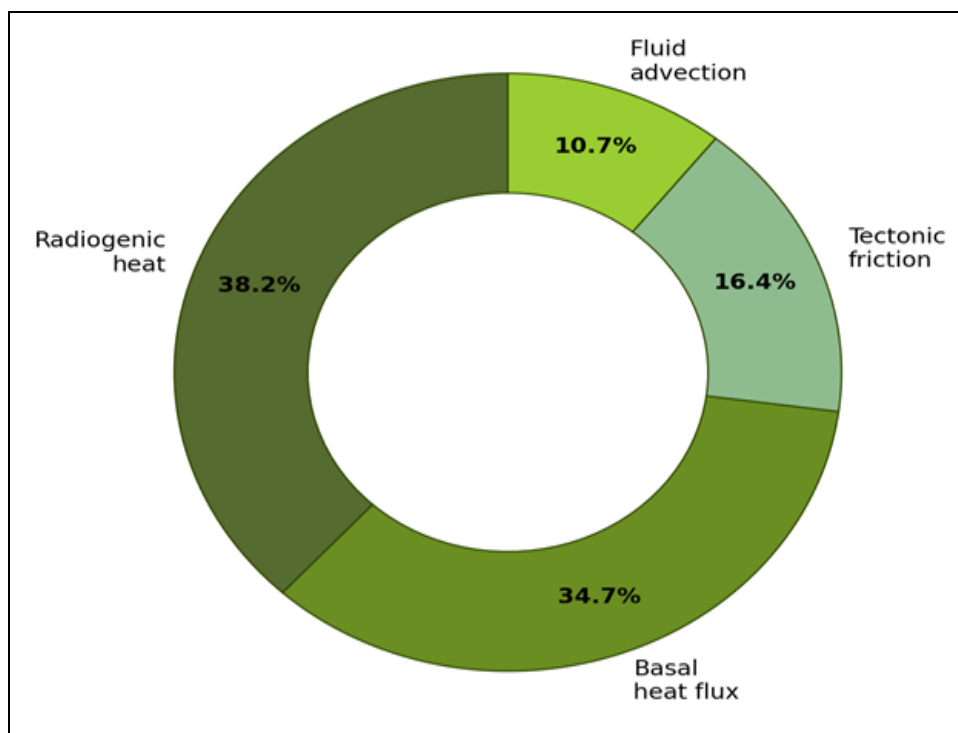


Fig 2: Estimated contributions to total surface heat flow in the Sichuan Basin from the one-dimensional steady-state model.

Radiogenic heat production (38.2%) and basal mantle flux (34.7%) together account for nearly three-quarters of the surface heat flow. Tectonic friction along the Longmenshan thrust adds 16.4%, detectable primarily in the northwestern foreland wells closest to the fault zone.

Discussion

The basin-wide mean heat flow of 67.4 mW/m² is 12% higher than the uncorrected estimate of 60.1 mW/m² published by Jiang et al. [3], and the difference is attributable almost entirely to the Horner correction, which added an average of 4.8 °C to raw BHT readings. This highlights the importance of proper correction before heat-flow compilation: uncorrected data systematically underestimate the thermal maturity of source rocks and can lead to pessimistic assessments of hydrocarbon generation potential [11].

The anomalously high heat flow above the Permian volcanic sequence has practical implications for geothermal-energy development. At temperatures exceeding 150 °C at 4,000 m depth (implied by a 36 °C/km gradient above a 15 °C surface temperature), binary-cycle power plants become economically attractive. The southwestern Sichuan basin, where the volcanic sequence is thickest and most radiogenic, may thus offer co-development opportunities: existing petroleum wells could be repurposed as geothermal producers once hydrocarbon reserves are depleted [12].

A limitation of the one-dimensional model is its assumption of purely vertical heat conduction. Near the Longmenshan margin, lateral heat transport from the uplifted crystalline basement of the Tibetan Plateau may contribute an additional 5–10 mW/m² that the model does not capture. A two-dimensional finite-element model incorporating the thrust geometry would be needed to isolate the tectonic-

friction contribution more reliably [13].

Conclusion

Horner-corrected bottom-hole temperatures from 72 wells across the Sichuan Basin yield a mean geothermal gradient of 30.6 °C/km and a mean surface heat flow of 67.4 mW/m²—both higher than previous uncorrected estimates. The Permian volcanic sequence in the southwestern basin records the highest heat flow (78.2 mW/m²), driven by radiogenic heat from pyroclastic units enriched in uranium and thorium. A one-dimensional model attributes 38.2% of total heat flow to radiogenic production, 34.7% to basal mantle flux, and 16.4% to tectonic friction along the Longmenshan thrust.

These results update the thermal framework for hydrocarbon-maturation modelling in the Sichuan Basin and identify the southwestern volcanic province as a zone of elevated geothermal potential. Future research should extend the dataset to include deep-borehole temperature logs with continuous recording, and should incorporate two-dimensional modelling to better constrain lateral heat transport near the Longmenshan margin.

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